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THE DIRECT CASTING OF STEEL STRIP

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THE DIRECT CASTING OF STEEL STRIP

SUMMARY

The process for making steel strip directly from liquid steel is placed in perspective with respect to the steel industry. The potential for minimizing the investment required for producing flat rolled products is explained and the economic benefits of such a process are indicated.

The various processes which have been studied over many years for producing thin slabs and cast strip are compared, and larger scale development programs which are currently being undertaken are described. The technical barriers which need to be overcome if any of these processes are to be applied on a large scale commercial basis are indicated.

It is concluded that thin slab casting, though the subject of major activity, particularly in the U.S., is not likely to bring as much economic benefit as a process to cast strip directly. While the casting of very thin strip is already applied commercially in the U.S. and Japan to produce narrow strip of ferrous alloys for electrical purposes, it is not suitable for producing a wide range of commonly used sheet products. Casting of strip in the range of 6 mm (1/4 in.) seems more difficult, but justifies major effort. With minimum rolling reduction, such strip could produce a major part of commercial sheet steel products. Among the processes examined, the casting of semi-solid metal (rheocasting) and the process of inside-the-ring casting are seen to have most potential for development of production facilities for the most useful thickness of cast strip. Even so major development work will be required.

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It is finally concluded that in view of the nature of the processes, any development program must include large scale testing in a production environment. In view of expenditures involved in carrying strip casting developments beyond the existing laboratory scale work, it seems necessary to examine the need for a consortium of steel companies working with the aid of Federal Laboratories, such as IMRI, to undertake such a program. As mentioned, incentives are great for introducing this technology with saving in production cost of strip of as much as $50/ton.

For the Canadian steel industry, strip casting could be a means by which the strong mini-mill sector could broaden their product base into flat rolled products. For the existing major flat rolled producers, strip casting provides a method for major cost saving in the face of increasing international competition.

THE DIRECT CASTING OF STEEL STRIP

A CRITICAL EVALUATION OF DEVELOPMENTS

1. INTRODUCTION

During the growth of the world's steel industry from the late 1800's into the first half of this century, the enterprises engaged in steel production were driven, due to demand and the "economics of scale", to build larger and larger steel plants which in turn led to building bigger individual production units. Steel plants grew in size so that facilities with up to 3 million tons/year were commonplace and production units for steel melting reached heat sizes of more than 300 tons.

Liquid steel was converted to products by casting ingots. Whether producing long products or flat products, the large size heats were accomodated by casting larger and larger ingots which in turn demanded huge multi-stand rolling mills to produce the multiplicity of bar, rod and sheet products, many of them having small cross-sections.

During the 1930's, the concept of producing smaller cross-sections (bar and strip) directly from liquid metal was considered for non-ferrous metals such as zinc, lead and copper. The idea of continuous casting of steel, although investigated, was found particularly difficult due to the higher melting point, higher specific heat and lower conductivity compared with the non-ferrous metals and alloys. By the 1950's, the majority of the world's production of aluminum and copper was converted from liquid to semi-finished form by continuous casting and there were many fully developed processes to produce the metals in small cross-section suitable for entering finishing mills to produce such products as rod and strip.

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In the late 1950's, continuous casting of steel, though the subject of considerable development work, was considered by much of the industry as a technical curiosity unsuited for the large-scale operations involved.

The compelling economics of being able to convert liquid steel into a semi-finished product (a "billet") suitable for entering a small bar mill prompted entrepreneurs to introduce the concept of the mini-mill. This involved the installation of a small electric furnace feeding a continuous casting machine making small billets which were rolled in a merchant bar mill to make merchant products (angles and reinforcing bar) for local markets. The economics of these mini-mills and technical developments permitting the production of more-and-more high quality products, has led to the situation where mini-mills now supply more than 30% of steel production of North America, principally as long products. Many of these mini-mill operations have shown that, due to lower investment cost per annual tonne of capacity and labour efficiencies possible in smaller operations without the need of enormous infrastructure,they have been able to compete with both the large integrated companies which in the past were able to demonstrate the "benefit of scale". Furthermore, mini-mills have been able to compete in some areas with imported steel which is produced with much lower labour rates.

In considering the future of the steel industry in the face of decreasing demand for tonnage, increasing demand for quality and international competition, the concept of the small scale "Market mill" making products for local industry would receive wider consideration if the ex isting mini-mill concept could be used to produce a full range of flat-rolled products in the way that today such mills produce most of the bar, rod and wire products. In fact, if the flat-mill mini-mill was technically and economically possible, it is probable that the concept might be adopted by some of the large integrated steel companies as a means of modernizing in small steps and improving financial performance.

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The obstacle to producing flat products on a small scale is the lack of economic technology for converting liquid steel into hot-band in small sized facilities. Until relatively recently, it was considered that required properties of flat rolled products, particularly for deep drawing applications could only be produced from processes using blast furnace hot metal, involving today high capacity oxygen furnace steelmaking. These high capacity plants were increasingly being equipped with large slab casters making slabs up to 12" thick. The huge slabs require the use of multi-stand semi-continuous or continous hot strip mills with minimum capacities of over 2 million tonnes per year and investment costs exceeding $300 000 000. Even when local markets are available to support these large facilities, the problem of accumulating blocks of capital to build new facilities are beyond the resources of most companies. Also, such facilities are likely to encounter problems in the face of wide swings in market demand.

Small scale production of flat rolled products exists in very few locations. Examples include:

- IPSCO in Regina producing skelp for welded pipe using scrap-based electric furnaces, ingots and a hot reversing Steckel mill producing mainly skelp for welded pipe.

- Sidbec-Dosco in Montreal producing a full range of flat products, hot and cold rolled from electric furnaces supplied with direct reduced iron. The facility uses slab casting and a Steckel mill for hot rolling.

In neither of these examples can the plants compete fully with a modern high speed multi-stand strip mill particularly with respect to hot rolled surface quality, hot rolled shape or product yield.

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Some of the limitations in flexibility of conventional hot strip mills and the desire to consider the technology for building smaller flat rolled facilities led to active study of the direct casting of thinner sections of steel in the early 1960's. This work initially considered adopting technology already well advanced in the non-ferrous field. Examples of casting equipment which were the machine developed by Southwire for casting copper and aluminum bar sections using a wheel and band, and the other was the Hazelett thin slab caster which used two belts. At this time, there was renewed activity examining the many ideas put forward for producing thin strip which could be found in the patent literature since Sir Henry Bessemer was granted a British Patent in 1865 [1]. (Fig. 1)

2. PROCESS ALTERNATIVES FOR THE DIRECT PRODUCTION OF SMALL CROSS-SECTION STEEL PRODUCTS

In reviewing process alternatives for direct production of steel strip, by-passing the existing process steps involving enormous primary manufacturing facilities, it is necessary to refer to technologies already explored for making both long (bar, rod and wire) and flat (sheet and strip) products.

This discussion will exclude examination of equipment for making heavy plate or structural products. The review will confine itself to processes which have the possibility of operating continuously. The advantages and disadvantages of each will be mentioned with respect to production of small cross sections. The discussion will cover casting processes which involved converting liquid metal directly into solid, and other processes including semi-solid (rheo-casting), liquid dynamic compaction (spray deposition) and powder rolling.

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2.1 Continuous Casting with Vertical Oscillating Mold

Conventional continuous casting with vertical oscillating mold does not have the potential for producing small sections due to limitations of means for steel feeding, low heat transfer and mechanical limitations on product extraction. However, it is noted that Noranda has a process for producing strip as thin as 12 mm (0.5 in.) up to 750 mm (30 in.) wide in copper and aluminum alloys [2].

2.2 Horizontal Casting

Current work on horizontal casting with static mold and intermittent withdrawal has future potential, because of lower capital cost for small capacity plants. However, this concept does not have the potential for producing small cross-sections at high linear casting rates.

2.3 Wheel Belt Casting

This technology has been widely applied in the non-ferrous industry for producing small billet sections for many years. The earliest patent is in 1887 [3]. A mold cavity is formed between a groove in a vertically mounted wheel and endless moving belt in contact with a length of the wheel circumferance. Wheel and belt are water cooled (Fig. 2).

Production machines have been operated since 1950 in Italy by Properzi to produce aluminum, lead and zinc wires. Southwire in the U.S.A. has operated machines since 1953 for aluminum and since 1965 for copper. This type of equipment has been used by Hitachi commercially since 1979 to produce a relatively large steel section of about 306 sq. cm. (40 sq. in.), but similar technology is offered by others to produce much smaller sections.

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Southwire has cast steel sections of 3 110 sq. mm. (4.8 sq. in.) at 14 m/min. (45 ft/min.) (Fig. 3) on a trial basis. Korf Engineering GMBH offers a machine to cast 14 400 sq. mm. (22.3 sq. in.) at 7 m/min. (23 ft/min.). These processes have the potential for making small cross-sections and similar concepts have been proposed to make thin slabs and strip.[4), 5)]

2.4 Twin Belt Casting

This concept, fully developed by Hazelett, has been widely used since 1963 [6)] for production of thin slabs and billets in aluminum, copper, zinc and lead with over forty commercial installations (Fig. 4). The equipment has been studied on a pilot basis for use with steel since the mid-1960's. Pilot installations were operated by Bethlehem Steel (1965-1969) and U.S. Steel (1967-1970) and other work was done by Oregon Steel (1965-1970) and the National Institute for Metals in Japan (1966-1970), all principally for carbon steels. Difficulties were encountered with slab casting less than 50 mm (2 in.) thick and non-uniform metal feeding caused quality problems with top surfaces. Though mechanically this equipment is capable of performing well, its potential for producing "strip" is unknown due to lack of suitable metal feeding techniques. Current programs to develop the Hazelett process will be discussed below (page 16). A listing of Hazelett installations is attached (Annexes 1 & 2).

2.5 Twin-Roll Casting

This process is specifically conceived for the production of strip. Originally patented by Bessemer in 1865 [1)], it was an invention ahead of its time since materials for steel handling and methods of control of melting conditions were not available. Even today, the principal problem is to devise a refractory system to bring liquid metal into the nip of the rolls. At the same time the

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rolls must withstand mechanical rolling stresses and intense thermal cycling. Many patents have been issued for this concept with steel being fed between the rolls from below or above (Fig. 5). Other arrangements include injection of the liquid metal horizontally. The extension of this concept to rheo-casting or casting in semisolid state will be mentioned later. (p.10)

2.6 Single Wheel Strip Casting

This has a number of configurations which use a cooled cylindrical surface. Liquid steel is brought to the surface where it is maintained in contact until solid and then stripped from the surface for subsequent processing.

Three principal processes are possible:

- Dip Casting
- Melt-Drag Casting
- Rapid-Chill Casting

2.6.1 Dip Casting

This involves the immersion of a rotating internally water-cooled cylinder in a liquid steel bath (Fig. 6). One sided solidification takes place to produce "strip" that is peeled from the cylinder as the solid steel emerges from the bath. This process is simple in concept but there are problems in maintaining uniform heat transfer over the contact area of the chill. This leads to major surface irregularities of the surface away from the casting drum. Also thermal cycling of the cooled drum leads to surface creep and distortion. Furthermore, maintenance of good edge condition of the cast strip is difficult.

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Extensive laboratory studies by Jones & Laughlin starting in the 1960's tackled some of these problems. Improvement in heat transfer uniformity was the subject of a patent in 1964 showing that, if surface texture could be used to reduce heat transfer, improved uniformity of strip was possible [7]. Evolving from this work, pilot scale trials were made with "inside-the-ring" casting which is described in several patents [8]. This principally solidifies strip on the inside surface of a drum and the solidifying strip is held in contact with the drum by a water cooled roll to maintain uniform heat transfer and improve the quality of the top surface (Fig. 7). The trials made rollable strip product up to about 300 mm (12 in.) wide. Work was discontinued in the early 1970's for unexplained reasons. However, it can be concluded that one reason may have been the fear that successful development would provide a tool for minimills to enter the flat rolled market.

It is claimed that the process can produce strip of about 5 mm thick, which on a casting drum 1 200 mm (48") wide, is a production of about 70 tonnes/hour. With a reduction ratio of about 2, hot band suitable for cold rolling could be produced using a simple 2-stand mill in line with the casting unit.

2.6.2 Melt-Drag Casting

This is a concept developed by Battelle Memorial Institute, Columbus, Ohio [9] and further developed by National Steel Corporation for carbon steels and by Allegheny Ludlum Steel for stainless steels. [10]

The liquid steel is delivered through a slot orifice to distribute it across the face of a rotating cooled cylinder

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so that a meniscus is formed between nozzle and cylinder, and surface tension forces "drag" the liquid from the orifice and distributes it uniformly on the cooled surface where it solidifies a uniform thickness strip. Experimental production using this process was announced by National Steel which has produced 115 mm (4.5 in.) wide strip up to 1.25 mm (0.05") thick at "hundreds of feet/minute". It is indicated that a plant making strip about 1 000 mm (39 in.) wide would have a capacity of 200 tonnes/hr. Scale-up on width is not seen to be a problem but it is difficult to produce strip up to 2.5 mm (0.1 in.) thick. For producing a reasonable range of products thickness, somewhat thicker strip is required.

Theoretical calculations show that strip 2 mm thick could be produced on a 1 m radius wheel at a rate of 5 m/sec. Accordingly, a machine 1 200 mm (48") wide could produce at a rate of 340 tonnes/hour.

2.6.3 Rapid Chill Casting

The process of solidify in metals in very thin foils on rapidly spinning surfaces has been developed for producing metallic glasses which have desirable electrical properties (Fig. 9). The process is in commercial operation in Japan. Allied Corporation in the U.S.A. pioneered work in this area and can produce metallic glass foils at 15-30 m/sec. (3 000-6 000 ft/min.). [11] This technique produces strip in range of 0.025 to 0.1 mm (0.001-0.004 in.).

Although lab experiments at MIT have produced strip up to 0.9 mm with this technique at substrate velocity of 0.6 m/sec. (120 ft/min.), scale-up to produce wide strip is seen to be difficult. [12]

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Furthermore, the thin gage product has excluded application of this process from serving a large part of the steel sheet and strip market.

2.7 Other Processes

Other processes have been studied and developed for by-passing the conventional casting/rolling process for the production of metal products from refined metals and alloys. The principal processes, in addition to direct casting, which might find application to production of steel products are:

- Rheo-casting or semi-solid casting and compaction.
- Liquid dynamic compaction or spray atomization/deposition.
- Powder rolling from spray atomized refined metal or from solid-state reduced ore.

2.7.1 Rheo-Casting

This is a process originally developed as a concept at MIT in a Ph.D thesis study on Sn-15% Pb alloy [13]. Extensive work since that time has included study of Sn-Pb, Al alloys, Cu based alloys, carbon steels and stainless steels. The process requires that the liquid metal to be processed be cooled to the point of initial solidification. It is vigorously agitated to break up the forming dendrites into fine spheroidal particles. The resulting slurry can be injected into a shaped mold or between rolls to complete the solidification. In the context of steel strip production, it is conceived that the semi-solid steel would be processed in a twin-roll unit, geometrically similar to that proposed by Bessemer [1] or in a wheel belt unit which is provided with a back up roll (Fig. 10).

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Conceptually, the idea is simple but the control of rheo-casting temperature and agitation to distribute the slurry uniformly across the face of a wire roll seems difficult. Furthermore, a means must be provided to assure that the semi-solid material is fed into the roll gap since roll/slurry friction would not be sufficient to maintain the rapid entry velocity required. Very high production rates are potentially possible even assuming the use of a single pair of rolls for compaction and solidification. For example, Flemings calculates that a production rate of over 700 tonnes/hr (800 tons/hr) is possible using 150 cm (5.91 in.) radius rolls producing strip 1 metre wide, 2.5 mm (0.1 in.) thick. This is a linear velocity of about 10 m/sec. (2 000 ft/min.), using 30 cm (12 in.) diameter rolls with a conservative assumption on heat transfer coefficient of 2 $cal/cm^2.sec.°K$ (14.74 $Btu/hr.ft^2.°F$). Multi-stand rolling is indicated to have a potential for even faster linear rates. It is evident that, at these very high rates, process control will be critical for such a process. Though rheo-casting is already applied to die casting and commercially for aluminum and copper, its application to steel is not far advanced.[14)]

2.7.2 Liquid Dynamic Compaction

This covers the technique of spray atomization of liquid metals and collection on a cooled surface (Fig. 11). A.R.E. Singer at Swansea University initiated work in the late 1960's on this concept. This led to pilot plant testing at Aurora Steel Co. [15)] in England. Other processes, such as the Osprey process has been used to make forging shapes, but it is claimed to be useful in making strip. [16)] (Also see p. 22 below.)

Experimental work at MIT, in which plates up to 1" (2.5 mm) thick were made, has shown that the fine grain structure obtained permits cold rolling without intermediate hot rolling. The process has the potential of producing "thin" strip in the useful range of 2-5 mm (0.08-0.2 in.).

However, no viable concepts for scaling up the process to produce wide strip have been presented although potential casting rates are likely to be similar as for rheo-casting, that is about 6 m/sec. (1 180 ft/min.) for 0.2 mm (0.08 in.) strip.

2.7.3 Powder Rolling

Although not strictly in the scope of this review, it is appropriate to refer to powder rolling as a means of direct production of strip. This is an old concept and is used commercially to produce metal strip for certain specialty products, for instance Canadian coinage.[17)]

The obstacle to its wide use for steel production has been the economics of producing suitable purity powder economically.

Two methods of powder production have been considered:

- Spray atomization from liquid steel;
- Direct reduction in the solid state of purified iron ore.

The economics of spray atomization is such that steel powder suitably sized for hot rolling mill costs as much as the present selling price of hot-band. One of the most ambitious programs on powder rolling of strip was initiated by American Can Company including a multi-million dollar pilot plant in Barrington, CT, leading to investigation

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of a major production facility in the mid 1970's. Steel industry economics led to a decision to abandon the project but renewed interest in promoting the concept was initiated by U.O.P. as recently as 1981.[18] U.O.P. planned to use gaseous direct reduction of purified iron oxide concentrates to produce powder which would be processed to strip using the American Can technology. (Fig. 12)

Earlier pilot plant work sponsored by Republic Steel at Ontario Research Foundation in the early 1950's involved the pre-sintering and reduction of up-graded iron ore concentrates on a moving belt and subsequent rolling compaction. The obstacle to acceptable strip properties was iron oxide purity. Other work has taken place at University College Swansea[19], in which organic bonded oxide pellets are reduced by gas in a rotary kiln and fed directly into a compacting rolling mill. Strip up to 100 mm (4 in.) wide and 2-3 mm thick (0.1") has been produced. The obstacle to commercial adoption remains the economics of producing sufficiently pure iron oxide concentrate.

A process related, in some respects, to powder rolling is the "Recon" process developed by General Motors. This used chopped high quality sheet steel scrap, which was enclosed in containers to exclude air and hot rolled to compact the contents. The compact could then be processed subsequently to produce sheet products. Extensive work in the late 1960's led to test work by several steel companies in the U.S. Difficulties in containment and absence of good concepts for a continous operation led to termination of the work. At one time, the idea of producing "flakes" by strip casting to provide additional raw material to add to manufacturing scrap for the Recon process was considered.

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3. CRITICAL EVALUATION OF STRIP CASTING CONCEPTS

It has already been mentioned that conventional continuous casting using a vertical oscillating mold and open pouring system does not have the potential for making thin sections due to low mold heat transfer and mold friction which would preclude the necessary fast withdrawal of product

The twin band process, such as Hazelett, is interesting in permitting frictionless product withdrawal. However, at present the process is not able to produce product reliably at thicknesses less than about 40 mm. While a section of 40 mm could be used as an entry bar for the finishing stands of a hot strip mill, thereby eliminating the investment in roughing mills, and decreasing the investment needed for slab heating, the Hazelett type process, at this time, is not able to produce a section thin enough to produce strip products without the need for major costs in hot rolling facilities. The same comments apply to wheel-belt processes, which are capable of producing billets (and slabs) with smaller crosssections than conventional continuous casting. It should be noted, however, that the principal problem of making thinner strip in either a twin belt or wheel-belt process relates to liquid metal feeding and distribution and not in the mechanical features of the casting machines.

Twin roll casting has the potential for producing strip in the range of 1-5 mm (.04-0.2 in.), permitting the direct production of a range of flat products without major additional rolling reduction. However, the methods of metal feeding and the mechanical design to resist the thermal cycling and mechanical loads have not yet been developed. It should be noted that the idea of rheo-casting in a twin-roll system is a very interesting concept, but its application to steel presents difficulties in materials handling and control.

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The various concepts of solidifying steel on the outer surface of a rapidly rotating drum have been widely studied. The production of very thin strip in the range of 0.1 mm (0.004 in.) in ferrous alloys in amorphous form for their magnetic properties is already commercial in widths up to 30 cm (12 in.). However, this rapid solidification technology is directly applicable neither to thicker strip nor to much wider widths needed for more extensive industrial applications. The melt-spinning process has also been developed to produce metal fibres which are used in composite materials.[20)]

The melt-drag process has the possibility of being able to produce somewhat thicker strip than the melt-spinning process and is the subject of active study.

4. CURRENT DEVELOPMENT PROGRAMS

Many millions of dollars have already been expended on strip casting and many millions more are being committed to a number of development programs. Information is available on work in Europe, Japan and U.S.A. Many of the steel companies in Japan have active laboratory programs and some pilot plant work. In Europe, there are several activities, some with Government support. In the U.S.A., there is Government support through the Department of Energy for two studies, and some privately sponsored work has led to plans for semi-commercial facilities.

Strong interest in these development activities is shown by the amount of discussion of this subject at the 5th International Iron and Steel Congress, Washington DC, April 6-9, 1986, at which two complete sessions were devoted to strip and thin-slab casting.

Summary information on a number of laboratory and pilot scale studies given below indicate the diversity of work, including those reported at the Washington meeting. While there may be other investigations in progress, it is believed that this summary lists most of the principal programs.

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4.1-4.6 United States

4.1 U.S. Steel Corporation and Bethlehem Steel Corporation

Following earlier work by both companies individually in the 1960's on the Hazelett thin slab caster, the two have jointly been successful in obtaining in May 1984 a development contract from the U.S. Department of Energy (DOE) involving an advance of $30 million in Federal funds over 5 years to develop thin slab casting. The objective is to produce cast product in the range 25.4 mm (1.0 in.) to 1.27 mm (0.5 in.). Work on casting will be undertaken in research facilities of the two companies with sub-contracted work by Hazelett Strip Casting Corp. on the casting machine, Harbison Walker Refractories on the steel feeding system, and Westinghouse on magneto-hydro-dynamic steel feed control system.[21] Initial work will cast slabs up to about 600 mm (24 in.) wide and will include trials with both horizontal and vertical configurations.

4.2 Armco/Westinghouse

This is a second major program supported by the U.S. DOE. It is a 2-year study directed to confirm the feasibility of the planarflow casting process.[11] Initial work was based on a 406-mm (16") dia. roll x 76 mm (3") wide with 180-270 kg (400-600 lb) heats. The metal pool is maintained in contact with the drum surface by an electromagnetic tunnel which stirs the metal and improves the top surface. The aim is to increase cast thickness up to 1.27 mm (0.05"). A larger pilot unit with 1 980 mm (78") dia. roll and 1 100 kg (2 500 lb.) melt is almost ready for trials.

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The strip produced to date shows potential of eliminating hot rolling with up to 27% of energy saving and major reduction in capital. Studies have included both Si-killed and Al-killed steels.

4.3 National Steel

Arising out a development agreement with Battelle Memorial Institute, National Steel has a trial program on melt-drag casting to produce carbon steel strip.[22] Laboratory facilities have made strip 1.27 mm thick by 114 mm wide (0.05" x 4.5") but the objective is to produce strip up to about 2.54 mm (0.1") thick. Extensive metallurgical examination of products has shown that acceptable product can be made with minimal cold reduction. However, it was evident that much larger scale test facilities will be required to develop metal handling and equipment for reliable continuous operation. It is understood that this program is not going to be continued.

4.4 Allegheny Ludlum Steel Corporation

Experimental work in Brackenridge extending over many years on thin strip casting and also using the melt-drag process[10] has led to successful production of cast stainless strip up to 35.5 cm (14 in.) wide in thicknesses from 0.5 mm (0.02 in.) to 1.3 mm (0.05 in.). Wheels with diameters 203 mm (8 in.) to 1 500 mm (59 in.) have been used with both copper and steel surfaces. After a minimum of cold rolling and heat treatment acceptable properties are obtained. Plans are being made to scale up the process to handle commercial sized heats.[23] This will be installed in Lockport NY and be able to handle 1.5-ton induction furnace heats to produce 560 mm (22 in.) wide product.[24]

Benefits claimed are lower capital and operating costs and less energy. New or modified alloys can be produced and secondary

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phase distribution is improved. Problems to be solved include tears, folds and surface scale. Internally, shrinkage cracks must be avoided. The aim is to control gauge to $\pm$ 3% which is acceptable for minimum cold rolling. No more than 65% cold reduction is needed for "conventional" properties. A range of austenitic and ferritic grades have been made successfully. The main objective was to make 1 mm thick strip but up to 2 mm is achievable. Scaleup of width leads to increased cracking. However, width up to 2 meters is considered to be possible.

4.5 LTV Steel

The individual companies which formed LTV Steel in 1985, namely Jones & Laughlin Steel and Republic Steel, had both been pioneers in research on the direct production of strip. In the 1950's and 60's, Republic conducted extensive work on direct reduction of ore super-concentrates, sintering and rolling. Initial pilot plant work at Ontario Research Foundation led to further work at the Republic research centre in Ohio. The work was terminated during the period when the U.S. Steel Industry was cutting back on entrepreneural investments.

J&L initiated a major laboratory research effort on direct casting of strip as early as 1964. Static dip experiments with metal chills with various surface textures, coatings and salt layers led to a concept of adjusting surface texture to achieve uniform solidification.[7] Initial indications that the thin cast sections could be rolled with a minimum of reduction to achieve good sheet properties, led to small scale pilot plant work in which a water cooled drum was immersed in a liquid steel bath. This was a concept which was an improvement to the invention of T. Sendzimir in Poland in 1932.[25]

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Test work with a 100 mm (4 in.) wide, 45 mm (18") diameter drum showed moderate success in producing strip sufficiently uniform to be hot rolled and permitted concepts of minimizing progressive distortion of the casting surface due to severe thermal cycling of the surface. Control of edge condition was particularly difficult. This led to the concept of inside-the-ring casting[8) 26)] which permitted better control of edge conditions and both surfaces. After a change in direction of the programme for an extended period while the General Motors "Recon" process was investigated, a pilot plant facility was constructed to test the 2-side casting technique. Trials were made in 1971 producing 305 mm (12 in.) wide material. After modest success and further confirmation that acceptable properties could be obtained and indications that width scale-up would not present problems, the program was terminated for reasons not explained. It can be concluded that the company was not willing to commit the large risk investment necessary to proceed with the next stage development since the introduction of radically new facilities was not consistent with immediate objectives of the company at that time. Furthermore, major integrated steel companies had a fear that mini-mills might make further inroads into steel markets if "compact" technology for making strip became available.

For 15 years, these developments have been in limbo. However, it is known that LTV, as successor to J&L, is re-starting lab investigations of thin cast steel sections and have instituted engineering study with Mannesman of possible pilot facilities with a view to a decision by the end of 1986 concerning a major program.

4.6 Nucor

Nucor which operates four mini-mill plants producing long products has announced plans to instal a 1 320 mm (52 in.) Hazelett machine

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to produce thin slabs for commercial quality sheet production for its internal production of roofing and decking and similar products. No information is available on the rolling facilities to be used to convert the thin slabs to sheet gauges initially. The intention is to instal the caster at the Darlington, SC, steel plant to develop casting practices for adequate product quality. By 1988, it is planned to be able to relocate the caster in a new plant to be built to produce flat products.[27] The Steckel mill and the Sendzimir planetary mill are both being considered for slab rolling in the future.

Nucor has estimated that using thin-slab casting, it can install a 500 000-ton/year facility for about $350 per annual ton as compared with $1 500 per annual ton for much larger conventional facilities.

The casting unit will be capable of operation of up to 100 tons/hr fed by a 32-tonne electric furnace, 18-tonne tundish and 4.26 meter (14 ft.) long Hazelett machine. A compression pinch-roll will be installed (as developed by Sumitomo). The novel tundish will have ASEA induction heating with 500 kW allowing temperature control to $\pm$ 1.6°C. The metal feeding system will be totally shrouded. Work with 1/2-scale water models has been used to develop designs for metal handling.

Metal feeding trials will start in August 1986 and slab casting is planned to start in November 1986.

4.7 Bethlehem/Armco/Inland/Weirton

This recently announced plan involves joint financing of work on the twin-roll casting technique based on earlier work by Bethlehem. No details on experimental facilities are available.

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4.8-4.11 Europe

4.8 Krupp

A Hazelett caster was installed in Duisburg, W. Germany in 1983 and a program, partly supported by ECSC and the W. German Research and Technology Department, has studied casting and rolling of thin slabs. The pilot unit can cast slabs up to 70 mm (2.75 in.) thick, 180 mm (7 in.) wide. Works has included both inclined and horizontal casting. The novel feature of some trials was the use of a closed system under pressure for metal handling which led to more uniform top surface. Casting rates of 6-8 meters/min. (220 ft/min.) have been achieved with 50 mm (2 in.) thick slabs. Future work must be directed to thinner wider product.

4.9 British Steel Corporation

Work since the mid-1970's with a 1/2-tonne pilot plant at the Teesside Laboratories on thin slab casting using a horizontal moving, "one-side" mold, led to building a 500-mm (19.6 in.) wide unit to make slabs up to 75 mm (3 in.) thick from 4-tonne heats. The series of trough shaped chills form a 14-meter (46-ft). Slab sections are cut-off, off-line for rolling. Uniform metal feeding and back-dam developments have permitted the production of product suitable for rolling. Various mold section coatings have been tested including ceramic "paper", ceramic washes, and carbon black. Casting rates of 20 m/min. (65 ft/min.) were achieved.

4.10 Voest-Alpine

An extensive pilot plant program is in progress on a single-roll caster 630 mm (25 in.) diameter, 1 200 mm (47,in.) wide. Trials

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to-date have used a 400-mm (15.7 in.) wide nozzle, but plans are made to test a 1 000-mm (39 in.) wide nozzle. The plant is supplied from 5-T ladles diverted from a 80-T BOF at Linz. The metal handling nozzle feeding the caster is about 6 mm (0.24 in.) thick and sheet is produced in the range of 3-5 mm (0.12-0.2 in.) thick at 3 m/sec. (120 in./sec.). It is notable that despite cut-backs in many areas, Voest-Alpine is pursuing this development energetically. It appears that the nozzle slot is spaced some distance from the casting roll but no details are available.

4.11 Mannesman-Demag

Mannesman-Demag signed an agreement in late 1985 with Osprey Inc., which is owned by Sandvik Steel (Sweden). M-D will develop and sell technology, on an exclusive basis, for flat product production, and on non-exclusive basis for special shapes and pipe using the Osprey spray casting process (see p. 11). A pilot plant to produce plates up to 1.2 m (47 in.) wide using 500-kg (1,100 lb.) heats has been constructed. It is indicated that a 2-stand densification rolling step would be needed commercially. This appears to be a process primarily for production of specialized products and not for tonnage strip production. The process is already used by Sandvik Steel to produce cast pipe 8 m (26 ft) long at a rate of 540 kg/hr (1 200 lbs/hr), which is then stretch-reduced to 14 m (46 ft).

4.12-4.17 Japan

4.12 Sumitomo Metals Industries Ltd.

Sumitomo has been experimenting with a Hazelett machine since 1982 which is capable of producing 600 mm (24 in.) product down

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to 40 mm (1.6 in.) thickness. Extensive trials using 30-tonne heats have been used to evaluate a range of grades of carbon and stainless steel.

The 2 900-mm (114 in.) long mold is mounted at a slope of about 6°and fed from a fully shrouded 2-tonne tundish. Casting rates of 4-6 m/min. (13-20 ft/min.) have been achieved. The 1.4 mm thick steel casting belts are coated with a 20 micron wash to minimize surface cracking. The machine has auto-start and automatic speed control and feed back to tundish level. The discharge pinch roll exerts a compressive force on the slab with a speed ratio of 1.015/1.0.

It has been decided to proceed with further development and an order has been placed for a 1 320-mm (52 in.) wide machine from Hazelett.

4.13 Kawasaki Steel

An experimental program has been run at Chiba since 1983. A twin-belt horizontal machine with fixed side dams is provided with in-line rolling. The machine can make product 10-30 mm (0.4-1.2 in.) thick by 100-150 mm (3.9-5.9 in.) wide fed from a 200-kg (441 lbs) induction furnace. Casting speeds in the range of 1.9-6.0 m/min. (6.2-19.7 ft/min.) were mentioned with a closed metal feeding system.

Separately, Kawasaki has a program with a twin-roll machine making silicon and stainless strip less than 1 mm (0.05 in.) thick.

4.14 Nippon Steel

Laboratory studies in the N.S.C. lab in Kawasaki are directed to finding more economic steel processing in competition with

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aluminium and plastics. A 300-mm (11.8 in.) diameter twin-roll (copper), 200 mm (7.9 in.) wide machine, fed from a 100-kg (220 lbs.) induction furnace has been used to study solidification on properties of strip about 1 mm (0.04 in.) thick at 30 m/min. (98 ft/min.). Model work has shown sensitivity of the process to under-cooling. To produce sound strip, working between the rolls must be avoided. There are no plans at present for pilot scale facilities.

4.15 Kobe Steel

Principal work has been directed to making ductile iron and high carbon (0.08%) steel sheet in the range of 2 mm (0.08 in.). The test unit is 70 mm (2.75 in.) wide fed from a 3-kg (6.6 lb) furnace. Extensive work has been done on relation between cooling rates and structure. In 0.8% C steel, a reduction ratio of 3 is adequate to remove the dendritic structure. No mention has been made of larger scale work.

4.16 Nippon Kokan

Experimental work using copper chills and also a twin-roll casting unit with 600 mm (24 in.) dia. rolls, 400 mm (15.7 in.) wide has been used to study solidification mechanisms. This has been supported by wax model simulations. This has permitted evaluation of acceptable separating force limits which can give stable casting conditions in twin-roll casting.

In the machine, a separating force of 2 tonnes is acceptable and not serious up to about 5 tonnes. However, if the separating force rises to 15 tonnes, continuous negative segregation is observed.

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4.17 Hitachi-Nischio Steel

A major program in Japan, indicated in the Hitachi Annual Report 1984-1985, involves a pilot plant fed from 15-tonne heats to produce strip 6-8 mm (0.24-0.3 in.) thick, 600 mm (23.6 in.) wide. It is operated in a fairly routine manner. No information has been available on the operating quality of product made and this work has not been widely known.

4.18 Other programs

Apart from the above studies, work is being conducted on aspects of direct strip production at a number of universities. Waseda University, Tokyo, has been studying thin sheet production since 1957 using a "Bessemer" type machine. Most recent work has used a machine with 200-(7.9 in.) rolls, 100 mm (3.9 in.) wide casting 1 mm (0.04 in.) strip at 12 r.p.m.

Prof. Singer at University College, Swansea, U.K., is continuing work on spray forming for strip production.

Work was sponsored by the US. DOE at MIT in 1982 on review of available technology for producing thin strip which pointed up the potential of rheo-casting (see p. 10).

At Aachen University, a one-wheel casting unit using 100-kg (220 lbs) heats is in progress supported by Thyssen, but there does not seem to be strong interest for commercialization due to excess strip mill capacity.

There are reports of other larger scale programs being planned, including one in India.

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new technology may be available to Canadian steel companies earlier than if the Industry waits until new processes are offered commercially.

In the absence of a major commitment of larger scale facilities, it is possible that there might be some interest on the part of the Canadian Steel Industry in cooperative research studies on the working and heat treatment of more rapidly solidified steel as produced in the types of processes discussed. Such work may be considered as a necessary preliminary to selection of strip casting processes for a certain range of products. This requires further discussion.

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5. TECHNICAL BARRIERS

From a review of the extensive work on methods for the direct conversion of liquid steel into small cross-section cast product, and specifically into strip product, it is evident that substantial fundamental information is already available. Also many systems have been studied on a trial basis. However, no systems have been scaled up to a size which would permit the production of wide material in sufficient quantity for even small scale commercial testing.

It is clear that the technology for the casting of wide thin slabs down to about 40 mm (1.6 in.) thick is already available. However, a thinner product would be required to derive major benefit from a decrease in subsequent rolling mill investment.

At the thinner extreme of cast strip thickness, commercial metallic-glass products are available in widths up to about 30 mm (12 in.) wide, but only in a thickness of about 0.1 mm (0.004 in.). Such product thickness has only limited application to the sheet steel market even if scale up to wider widths can be achieved.

The most useful cast thickness from a view point of extensive commercial application is in the range from about 2.0-10 mm (0.08-0.4 in.) in widths of about 1-2 m (40-80 in.). Technically, this seems to be the most difficult range of thickness for direct casting to produce uniform and high quality surface. However, it is indicated that in this thickness range, very high casting rates per unit of width can be achieved. Furthermore, initial work indicates that useful properties in sheet products can be obtained from these thicknesses with a minimum of rolling reduction and heat treatment.

In order to identify where technical effort should be made in order to advance the development of means for the direct production of strip, it is useful to define the barriers which exist to the successful implementation of the various production concepts.

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TABLE 1

RANGE OF CASTING RATES

Process	Strip Thickness		Casting Speed		Production Rate (1 metre, 39" wide)	
	mm	in.	m/min.	ft/min.	T/hr	NT/hr
Slab Casting a)	250	10	1.5	4.9	176	195
Thin Slab (Hazelett) b)	40	1.6	3.8	12.6	73	80
Strip Casting (J&L) c)	5	0.2	23	76	54	60
Strip Casting (Inside-the-ring) c)	5	0.2	46	152	104	120
Melt-Drag (National) d)	2	0.08	300	984	282	313
Rapid-Chill (Allied) e)	0.1	0.004	914	3,000	43	48
Liquid Dynamic Compaction f)	2	0.08	360	1,170	338	372
Rheo-Casting (Flemings) g)	2.5	0.1	600	1,960	705	782
Powder Rolling (Amer. Can) h)	1	0.04	61	200	29	32
Reduced Ore (Singer) i)	2	0.08	12	39	11	10

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The areas of technical development required, if discussion is confined to conversion from liquid steel into strip product, are:

- Liquid steel
- Liquid Steel Handling
- Casting Equipment
- Product Properties

5.1 Liquid Steel Production

Techniques increasingly used in quality steel production at the present time provide the means to deliver liquid steel to a strip casting machine at the correct temperature and precise composition. These techniques include selection (residual control) of raw materials, ladle furnace practices including vacuum and heating, injection methods and stirring. Because of the extreme importance of avoiding large exogenous inclusions, it will be useful to advance the development of filtering technology so that filters can be incorporated in liquid metal delivery systems.

It should be noted that precise temperature and composition will be essential to assure stable conditions in any high speed casting process. Also, it is possible that steel compositions may need to be modified to achieve appropriate conditions during casting and to obtain required product properties.

5.2 Liquid Steel Handling

In the past, a serious obstacle to the success of thin section continuous casting was the lack of suitable materials for constructing steel holding and distribution equipment for delivering liquid steel uniformly to the cooling surface.

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In the 1960's, when work on the Hazelett caster was active, the principal problem was uniform steel distribution, even when making slabs no thinner than 50 mm (2 in.). Recently, major progress has been made in refractory materials which are both resistant to erosion by liquid steel and mechanically strong. Accordingly, the prospect of designing nozzles, launders, tundishes, etc. with good dimensional stability is much improved. One example of recent progress is development of sialon/boron nitride composites. Certain such ceramic parts are now available commercially from Nippon Kokan (NKK)[30] having excellent toughness, and better oxidation and corrosion resistance to steel than silicon nitride. Despite progress in this field, more work is necessary to develop materials for steel handling suitable for extended periods of continous operation. The potential exists for combining properties of strong engineering ceramics in composites with materials resistant to liquid steel.

Even with precise control of steel temperature and composition and precise dimensions of nozzles, uniform steel distribution across wide widths is extremely difficult. For this reason, consideration is being given to electromagnetic control for metal flow as well as for shaping the metal stream during casting. This technique was originally developed in USSR for casting aluminum [31] and it is now widely used commercially for aluminum and is being explored for copper.[32] Among the programs being supported by U.S. DOE, Westinghouse is working with the U.S. Steel/Bethlehem consortium to contribute expertise on MHD steel feeding systems.

Westinghouse is also providing MHD technology to Armco to create an electromagnetic tunnel to hold solidifying metal in contact with the casting drum in planar-flow casting in order to make thicker strip (up to 1.2 mm or 0.05 in.).

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Already British Steel Corporation in its patent[33] had proposed the use of an electromagnetic device to stop back-flow at the liquid steel feed point in its horizontal casting process, although this is not being used.

In laboratory scale work at MIT, supported by AISI, on rapid chill casting on a single wheel, the favourable effect of magnetic field on casting uniformity was demonstrated. A theoretical analysis was made in an attempt to define how the field modifies the shape of the liquid stream in contact with the rotating chill substrate.

It is evident that this whole subject of liquid metal stream modification and control by means of electromagnetic fields is a very fruitful field of study and probably an important key to any successful wide strip casting process.

5.3 Casting Equipment

5.3.1 Heat Transfer

The function of casting equipment is to provide a moving cooled substrate against which liquid steel is brought into contact so that latent heat of fusion is removed from the steel.

The important design factors are heat transfer, heat transfer coefficient and contact time. Work on strip casting to produce strip of intermediate thickness has shown that uniform solidification across the casting surface is possible if heat transfer is moderated either by coating or by texture on the surface of cooled substrate. Exact relationship between metal circulation at the casting surface and surface properties are not well known. These

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require further study. Also, unless steel super-heat is very well controlled, major variations in solidification rates will be evident. These will require means for varying casting speed. Steel superheat will vary with a combination of temperature and composition. Allowable variations for a particular casting process are not known.

It does not seem likely that temperature/composition control will be especially critical in the case of thin slab casting. However, with strip casting, rapid chill casting and in rheo-casting, precision is likely to be essential.

In the case of rheo-casting, enormous differences in viscosity can be expected with relatively small changes in residual super-heat. For AISI 440 stainless, a change of volume fraction of solids from 0.45 to 0.55 can result in a 5-fold increase in viscosity.[34].

5.3.2 Mechanical Design

For casting thin strip, the dimensional relation between the steel feeding surface and the moving cooled substrate is critical. This is especially true for the melt drag or the planar flow systems. This requires dimensional stability of the refractory nozzle or electromagnetically controlled stream, but also uniform linearity of the casting surface or surfaces. At steel casting temperatures, the thermal cycling of the immediate surface of a chill is very great, leading to surface creep. Design means must be found to eliminate or compensate for this surface creep.

Design ideas which have been tested included slotted surfaces, metal ceramic composite surfaces, surfaces which are heated, and various means of mechanical support (especi-

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ally applicable to the belt machines). At present, no totally successful casting surface has been developed which is likely to provide many hours of continuous operation. This is a field for development and testing.

5.3.3 Speed

The need for speed adjustment to maintain constant conditions at the casting point has been mentioned. The critical element for speed control is a suitable sensing device at the solidification point which can provide feed back to steel flow control or to the casting surface drive.

Recognizing the difficulty in providing good level control in conventional continuous casting, it is certain that this problem must be investigated actively.

5.3.4 Dimensional Adjustment

The question of adjustment of casting thickness and width always arises when discussing the future application of strip casting to a range of commercial products. Recognizing the critical nature of both steelmaking and casting in any existing concept for strip casting, it seems most appropriate to design a machine for a single width and thickness, making the required finished product range by appropriate rolling and slitting.

Not enough is known about any of the processes under study to know whether it is feasible to provide flexibility of changing strip thickness. The possibility of changing strip width off-line or on-line will depend on the type of process.

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5.4 Materials Properties

5.4.1 Cast Structure

In the case of a dip process such as a rotating cooled drum immersed in a liquid steel bath, the cast strip solidified from one side only will reject solute elements into the bath so that the concentration of these elements, such as carbon and sulphur, will build up in the bath until concentrations of solute element are sufficient that the rate interdendritic entrapment of these elements will equal the rate of rejection from the dendrites. The extent of this problem is not known since the composition of the fine structure of rapidly solidified commercial compositions has not been sufficiently studied.

In the case of two-side casting (such as inside-the-ring casting) or in any of the flow casting techniques, solute rejection is not a consideration.

The most important features of cast structure in thin strip casting are mechanical integrity and smooth surface, both of which are essential for producing a usable sheet product with minimum rolling reduction.

To assure absence of cracking, it requires careful mechanical handling when removing the cast strip from the substrate.

In line "hot rolling" may require careful reheating to avoid intergranular cracking in the case of aluminum killed steels. This is a problem already observed in direct rolling of continuously cast slabs where partial cooling of the surface resulted in rejection of aluminum nitride

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at grain boundaries. It is possible that some composition modification may be required to assure in line rollability of some grades.

Rapid cooling results in very fine grain structures. Extensive work on the properties of rapid solidified strip has already shown the favourable effects of these structures in both crystalline and amorphous materials.[35) 36)] These include better toughness and hot workability and ductility. In the case of alloy steels, leaner composition can be used to achieve equivalent properties. Some improvement has been observed in corrosion resistance of stainless steels.

Further work is required to explore the effects of rapid solidification on the full range of commercial carbon steels in sheet products.

5.4.2 Rolled Structure

Some very rapidly cooled ferrous alloys have sufficient ductility in the cast state to be used directly in some forming operations. This only applies to very thin strip. At intermediate thickness (above about 1 mm or 0.08 in.) some cast material can be cold rolled without intermediate heat treatment. At a thickness of 12.5 mm (0.5 in.), it is possible that material will require some hot rolling prior to further processing.

Within this general range of thickness, it has been found that reduction ratios of as little as 2:1 are sufficient to produce a fully wrought structure in steel strip at least in low and medium carbon steels. This is due to the extremely fine grain structure obtained during fast solidification.

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This observation on reduction ratios is consistent with recent conclusions from the use of electromagnetic stirring in billet casting.[37)]

Further laboratory work is required to define the relation between solidification rate and required reduction ratio, both hot and/or cold, to achieve required product properties.

5.4.3 Heat Teatment

In addition to the variables of solidification rate and rate of hot working, further work is required on the effects of time/temperature history during processing of strip cast material. Conventional data on hot rolling, annealing and cold rolling do not necessarily apply. An organized program of research is required in order to define the range of steel composition required to meet the full range of sheet product applications.

The factors to be considered are surface texture, formability, drawability, ductility, strength, toughness and hardness.

6. CONCLUSION

In the rapidly developing field of strip casting, there are large gaps in knowledge of materials behaviour. This relates both to materials of construction for casting equipment and in properties of steel for sheet production.

In the field of casting processes themselves, there are major design problems to be solved in the construction of pilot plants. Pilot plants

of substantial size are required to permit valid test of concepts on a sufficient scale to give confidence that production scale machines can be built.

To date, no pilot plant has been built which is large enough to permit testing of any of these processes where component performance can be assessed under production conditions. To put this into perspective, a process such as the melt drag process which could produce 1-m strip at 280 tonnes/hr would only operate for 20 minutes if supplied with a 100-tonne heat. In a pilot plant environment with say a 10-tonne heat, the running time would only be 2 minutes.

The general conclusion is that substantial fundamental work remains to be done on aspects of thin strip casting. Furthermore, in order to make progress towards developing reliable production processes, it is evident that multi-million dollar commitments must be made for building test facilities in a full scale production environment.

Regarding the choice of the most favourable processes, the most immediate progress seems likely in the production of thin slabs by the Hazelett process, although it is not clear whether it will be possible to make slabs thin enough to avoid a costly multi-stand or multi-pass hot rolling mill.

Inside-the-ring casting has interesting potential for making intermediate thickness cast strip suitable for processing to a wide range of sheet products. Further development would require the investment in a major test facility.

Melt drag casting has alrady been shown to be capable of producing good quality strip on a small scale pilot basis. Scale-up on width seems feasible but, unless it can be demonstrated that strip of at least 2 mm (0.08 in.) thick can be produced reliably, the process will have limited application for many sheet products.

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Rapid chill casting may be capable of scale-up in width. However, it will not be useful for wide commercial application since it will only produce very thin products. It may find a use to produce strip products for use in composite "sandwich" materials.

Rheo-casting seems to present one of the most interesting possibilities of making near net shape products in either long or flat products in a range of thicknesses. It has the possibility of producing materials directly with interesting properties. However, success with this process depends on development of reliable techniques for producing and feeding the semi-solid steel slurry between forming rolls at very high rates. In addition, it will be difficult to design a system to withstand the thermal cycling and mechanical stresses which will be encountered.

7. ECONOMIC IMPACT OF STRIP CASTING ON THE STEEL INDUSTRY

The overall capital cost for an integrated steel plant including requirement for iron ore, coke, blast furnaces steelmaking, rolling and finishing facilities exceeds $1 500 per annual ton of capacity in the steel plants in the size range of 2 million to 4 million tons per year. The investment cost of a modern semi-continuous strip mill with a capacity of over 2 million tons per year will exceed $400 000 000. A slab caster capable of casting about 1 million tons per year will cost over $100 000 000.

No detailed design information is available on complete casting facilities based on any of the new strip casting concepts. However, in considering the size of equipment involved, it is difficult to believe that it would exceed $15-$20 million for a unit to produce say 1 250 mm (50") wide strip to produce 500 000 tons per year. It appears that investment in strip casting would be less than half that required for conventional slab casting.

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Regarding operating cost, the DOE proposal from U.S. Steel/Bethlehem estimated that, even making thin slabs rather than the more advantageous but more difficult thin strip, savings of $35-$45/ton should be possible which includes a 30% saving in hot rolling cost. Nucor, for similar technology, mentions anticipated savings of at least $40/ton. This must be related to the production of products selling for about $400/ton.

For the more ambitious technology, it is difficult to make good estimates on total cost savings since many of the processing parameters, particularly in annealing and cold rolling, have not yet been defined. However, an analysis of energy use for strip casting and processing as compared with conventional processing to the same cold rolled products has indicated that the strip casting route would save 75% of annealing energy and 50% of the rolling energy. Conventional processing used about 10×10^6 Btu/ton, of which about 3.6×10^6 Btu/ton is metal working energy and about 7.0 million is annealing energy. Thus strip casting should permit processing with only about 3.5×10^6 Btu/ton or a total saving of about 70% of the strip processing energy.

With the potential savings in both capital and operating cost, if technical means can be developed for direct casting steel strip, it is certain that the opportunity to implement the new technology would be preferred over the opportunity to increase plant size.[38] However, the use of this new technology by existing large integrated steel mills, with major investments in large strip mills already spent, will imply a major change in direction. For the mini-mills, the introduction of strip casting would be a means to expand their product range.

This does not imply that this technology will necessarily be introduced very fast by mini-mills since they do not have the financial resources to commit major risk investment for such a development. Large companies are more likely to be able to expend the development funds, but may not be motivated to do so.

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A more likely chance to succeed in such a development resides in cooperative development activity such as has been intiated recently by the American Iron & Steel Institute and US Federal Agencies. This is allowing major programs to be launched on several process routes. Such cooperative programs might be initiated in Canada where the minimill sector is an important part of the industry. It is also possible that the integrated companies would participate in order to protect their longer term objectives towards continued international competitivity.

In the face of competitive pressures, it appears desirable to explore whether a consortium of Canadian Steel Companies could be formed to undertake a national effort on strip casting with the cooperation of the Federal Government, in which IMRI could play an important role. The only alternative for the individual Canadian steel companies, if they are not to be left behind, is to seek, individually, partnerships with U.S. or Japanese companies already actively engaged in this field.

8. RECOMMENDATIONS

Before embarking on a major research study in the laboratory on aspects of strip casting, it is recommended that IMRI should evaluate the interest on the part of the Canadian Steel Industry in a cooperative program having a medium-term objective of operating a major in-plant development facility. If interest is evident, a working group would be required to identify the most promising technology and to plan development activities including supporting laboratory activities.

Without a substantial financial commitment for an extended period, it will not be possible to make substantial progress towards a practical production process for the more economic manufacture of steel strip.

The only alternative to an independant Canadian program, would be to participate financially in development programs alrady in progress elsewhere and to undertake supporting technical studies. In this way,

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TABLE 1 - NOTES

COMMENTS ON STRIP PRODUCTION RATE

a) Maximum linear speed reported for conventional continuous casting is about 10 m/min. (33 ft/min.) for 50 mm (2 in.) square sections. However, this technology is not applicable to wide slabs. Casting rates for 250 mm (10 in.) slabs do not commonly exceed 1.5 m/min. (4.9 ft/min.).

b) The casting speed of the twin belt caster is strictly related to mold length. A casting rate of 73 tonnes/hr (80 NT/hr) for 1 metre width assumes a 4 m (13 ft) long mold.

c) Casting speed of a single side chill is based on work by J&L. It has been indicated that the heat transfer in an inside-the-ring caster with cooling roll increases casting rate by a factor of two.

d) Melt drag casting has only been tested on strip up to about 1.3 mm (0.05") thickness. Assuming it is possible to reach 2 mm (0.08"), the casting rates given are derived by calculation assuming a casting wheel of 2 000 mm (78 in.) diameter.

e) Rapid chill casting rates are based on quoted linear speed from Allied Chemical and Hitachi.

f) Liquid dynamic compaction casting rates are assumed to be similar to those achievable with rheo-casting since, as in rheo-casting, a significant part of the latent heat of fusion is removed before the metal being cast reaches the cooling substrate.

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g) Rheo-casting production rates are related to the surface contact area maintained for cooling and forming the semi-solid material. The rates quoted are based on calculations by Flemings from data on laboratory equipment and commercial operations with non-ferrous metals.

h) Powder rolling production rates are based on pilot plant work by American Can. Limitations on powder compaction rates are related both to powder feeding and escape of gas from between powder particles during compaction.

i) See ref. 19).

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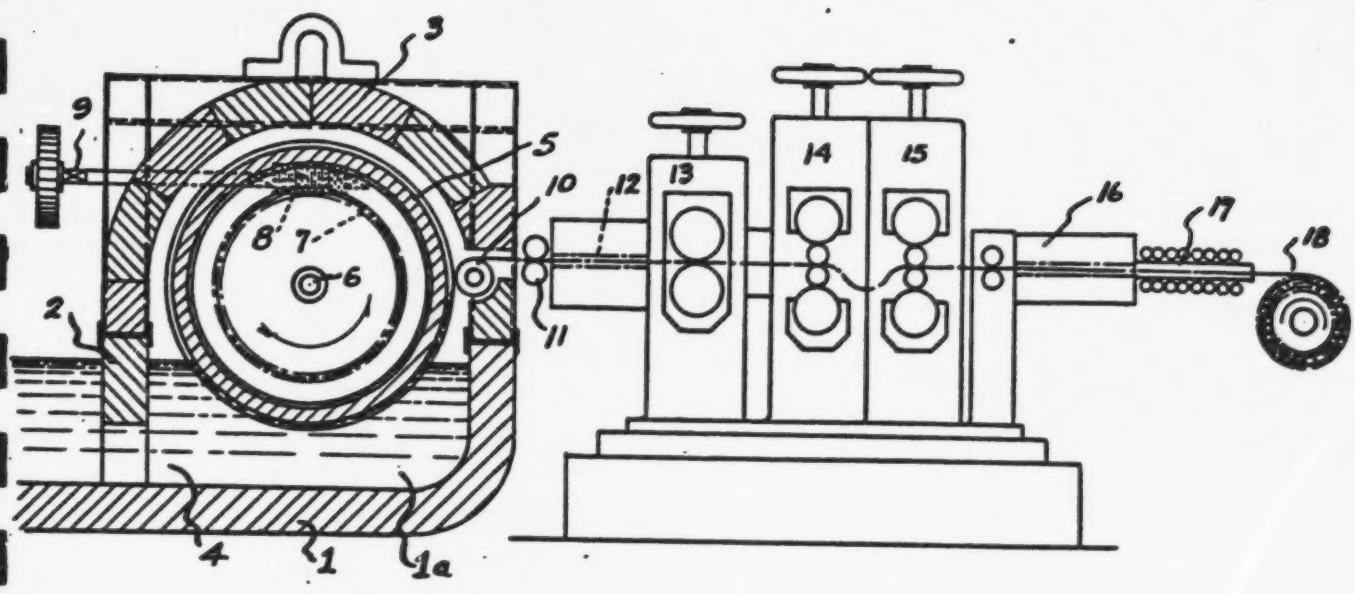

Figure 6

Dip Casting 25)

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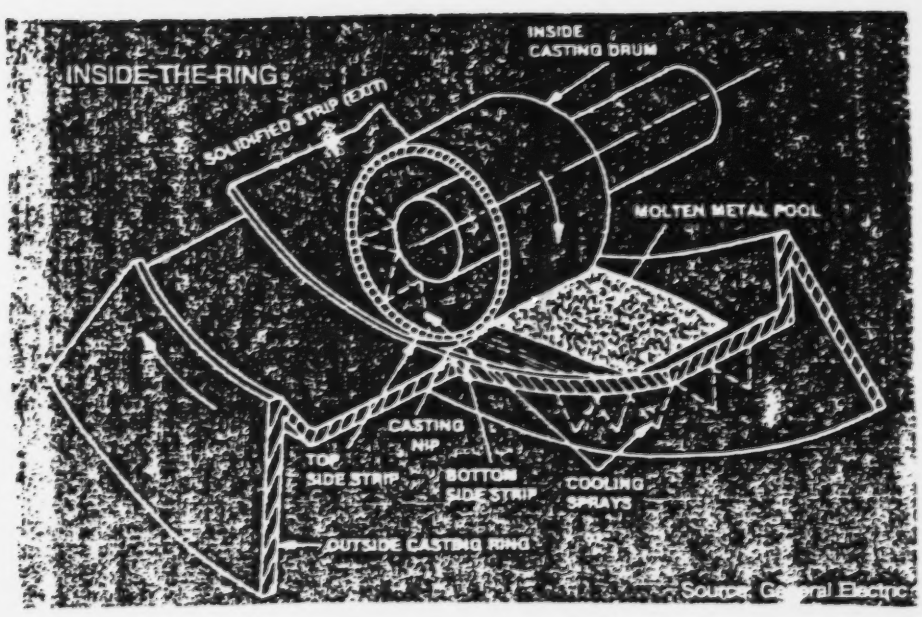

Figure 7

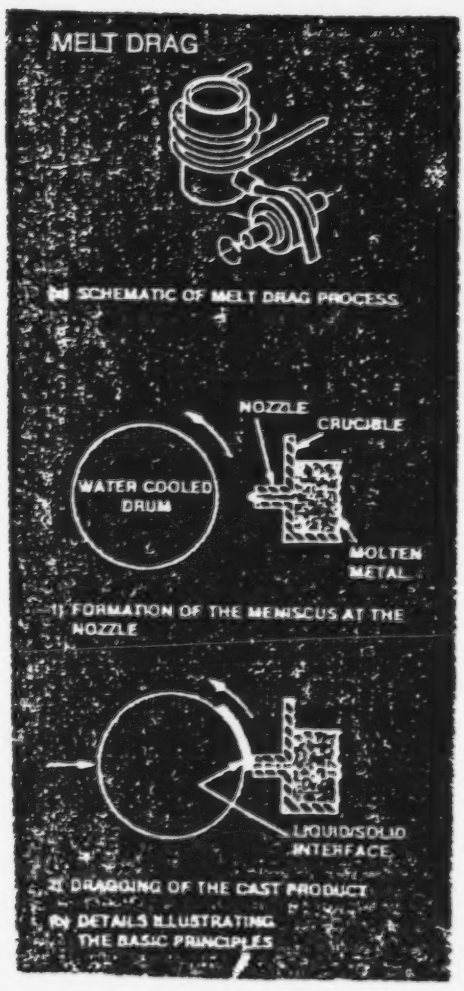

Figure 8

Hazelett STRIP-CASTING CORPORATION

TELEPHONE (802) 863-6376
TELECOPIER (802) 863-1523

MALLETTS BAY
POST OFFICE BOX 600
COLCHESTER, VERMONT 05446

TELEX 954638
CABLE: HAZELETT BURLINGTON VERMONT

PILOT CASTING INSTALLATIONS - FERROUS

Company	Product	Machine	Date
Bethlehem Steel Corp. Bethlehem, PA	Al-killed	Model 20 30" Wide	1965-69
Oregon Steel Mills Portland, OR	Silcon-killed	Model 20 30" Wide	1965-70
National Research Institute for Metals Meuro-ku, Japan	Silicon-killed	Model 20 12" Wide	1966-70
United States Steel Pittsburgh, PA	Silicon-killed	Mod. 20.101 30" Wide	1967-70
Ugine Kuhlmann France	Stainless Steel	Model 22 51" Wide	1969-73

RESULTS OF FERROUS PILOT CASTING INSTALLATIONS

I. BETHLEHEM STEEL - 1965-69

The operation and results are detailed in a paper, "Continuous Casting of Low-Carbon Steel Slabs by the Hazelett Strip-Casting Process," by B.C. Whitmore and J.W. Hlinka, presented in 1969 at the annual AIME conference in Toronto. Briefly, 124 casts of low carbon, aluminum-killed slabs ranging in thickness from 1" to 6", and from 10" to 24" in width were made. The summary states "machine operation was good and attention was required only for routine mechanical maintenance and belt replacements;" and "no burn-throughs (of the belts) were ever experienced."

The metallurgical condition of the slabs was not satisfactory, however, due to heavy concentrations of segregating oxides trapped during solidification about 1/2 to 3/4 inches below the top surface. The project was discontinued when the investigators concluded that "continuous casting of AK steel in an inclined mold is impractical when the final product must have good surface condition."

In a separate program a number of 3 x 10" slabs of stainless steel Type 302-304 were made for Carpenter Steel, who rolled them down to .090" and .025" strip. The bottom surface was quite satisfactory while the top surface contained some inclusions. The cross section was sound. Samples of this material are available at the Hazelett plant.

II. OREGON STEEL MILLS - 1965-70

The results of the Hazelett casting program are described in a paper, "Operating Practice, Continuous Pressure Pouring and Hazelett Casting at Oregon Steel Mills," by J.B. Allyn and A. MacDougall, presented before the A.I.S.E. Conference in Cleveland in 1972. From November 1969 through April 1970, a total of 1000 NT of structural grade billets were cast in two sizes, 5½ x 10" and 4 x 8". Production capability was limited by molten metal availability.

Product quality was good with little internal porosity and few tears. Little chemical segregation was detected, and inclusions were evenly distributed with no evidence of flotation toward the top surface. About 300 tons of the product were rolled into rebar with satisfactory results.

The pilot operation was discontinued after the successful demonstration of the commercial practicality of the process for casting steel.

III. NRIM - 1966-70

The comparatively narrow machine was used for the test casting of small slabs 2" thick by 10" wide. Steel types were AISI 1030 and AISI 1060 silicon killed. In addition, small lots of Type 304 stainless steel were cast whose quality was said to be excellent.

Carbon steel quality was described as "satisfactory", although some tendency exists for the non-material inclusions to segregate in "the middle of the upper half of the slab cross section." The macrostructures indicate a "very fine regular system." The surface was said to be "good-looking" when the turbulence of molten metal entry is minimized.

This pilot line was discontinued when research funds were exhausted.

IV. U.S. STEEL RESEARCH LABS AT SO. CHICAGO - 1967-70

After initial trials, a total of 35 casts of low carbon, RIBAND steel, a patented analysis developed by USS for their large slab caster at Gary was made. This analysis contains .08% carbon max., .50-.70% manganese, and .06-.09% silicon plus a small aluminum addition. Size of slab was 3 3/4" thick by 30" wide. Caster operation was satisfactory, similar to that experienced at Bethlehem, except for a number of breakouts in the secondary cooling downstream from the caster.

The cast slabs were hot and cold rolled to .060" thick and inspected. The surfaces were generally unacceptable due to random slivers. Scarfing of the slabs before rolling did not eliminate the problem.

In 1970 the development of the USS vertical oscillating caster was complete and U.S. Steel discontinued research work on other competing processes including the Hazelett.

V. UGINE KUHLMANN RESEARCH LABS AT ARDOISE, FRANCE - 1969-73

This caster was purchased for a large research effort on specialty and stainless steels, and was designed to cast slabs about 42" wide and 4 3/4" thick. Actual operation was limited to single slabs of Type 304, 21 feet long weighing about 6 NT.

The product exhibited satisfactory bottom surface and cross section, but the upper surface contained a layer of inclusions to 1" below the top. This was generaly attributed to the metal feeding problems.

Due to a change in priorities and shortage of research funds, the project was shut down for an indefinite period when research funds were limited.

C.J. Petry

CJP/mm

STRIP-CASTING CORPORATION

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TELEX 954638
CABLE: HAZELETT BURLINGTON VERMONT

CONTINUOUS CASTING INSTALLATIONS

ALUMINUM

Date	Company & Location	Cast Width	Caster	In-Line Rolling Mills
1963	Aluminum Company of Canada Toronto, Ontario CANADA	20" (510mm)	Model 14	ALBERT MANN Single Stand 2-High
1969	Aluminum Company of Canada Arvida, Quebec CANADA	60" (1525mm)	Model 15	DEMAG 3-Stand Tandem 2-High 4-High 4-High
1970	Nihon Atsuen Kogyo, K.K. Itami Hyogo-Pref. JAPAN	12" (300mm)	Model 20	ALBERT MANN 2-Stand 2-High
1979	Alflex Corporation Carson, California U.S.A.	24" (610mm)	Model 20	LEWIS 2-Stand 2-High
1983	Barmet of Kentucky, Inc. Livia, Kentucky U.S.A.	14" (356mm)	Model 20	WATERBURY FARREL 3-Stand 2-High
1984	Alpase, Inc. Downey, California U.S.A.	50" (1270mm)	Model 15	None [Tooling Plate]
1984	Nihon Atsuen Kogyo, K.K. Itami Hyogo-Pref. JAPAN	18" (450mm)	Model 20	ALBERT MANN 2-Stand 2-High
[1985]	Barmet Industries Uhrichsville, Ohio U.S.A.	52" (1320mm)	Mod. 23.75	MESTA 3-Stand 4-High
[1985]	Advanced Aluminum Products Hammond, Indiana U.S.A.	29" (737mm)	Model 20	3-Stand

CONTINUOUS CASTING INSTALLATIONS

COPPER ROD

Date	Company & Location	Billet Section (Millimeters)	Caster	In-Line Rolling Mills
1972	Met. Hoboken-Overpelt Olen BELGIUM	60 x 130	Mod.20.146	KRUPP 15-Stand Continuous Rod
1975	ASARCO, Inc. Amarillo, Texas U.S.A.	60 x 125	Mod.20.146	KRUPP 15-Stand Continuous Rod
1976	Met. Hoboken-Overpelt Olen BELGIUM	70 x 130	Mod.20.146	KRUPP 15-Stand Continuous Rod
1979	Glogow Copper Works Orsk, Lubin POLAND	50 x 120	Mod.20.146	KRUPP 15-Stand Continuous Rod
1978	Metalrame, SpA Avellino ITALY	50 x 120	Mod.20.146	KRUPP 15-Stand Continuous Rod
1978	AT&T Nassau Metals Corp. (Div. Western Electric) Gaston, So.Carolina, U.S.A	60 x 120	Mod.20.146	KRUPP 15-Stand Continuous Rod
1978	Thomson-Brandt Chauny FRANCE	60 x 120	Mod.20.146	KRUPP 15-Stand Continuous Rod
1979	Electronum Zalau ROMANIA	50 x 50	Mod.20.112	KRUPP 10-Stand Continuous Rod
1980	Phelps Dodge Corp. Norwich, Connecticut U.S.A.	60 x 130	Mod.20.146	KRUPP 14-Stand Continuous Rod
1980	Sumitomo Electric Indus. Osaka JAPAN	60 x 120	Mod.20.146	KRUPP 13-Stand Continuous Rod
1982	Caraiba Metais, S.A. Salvador, Bahia BRAZIL	50 x 125	Mod.20.146	KRUPP 15-Stand Continuous Rod

CONTINUOUS CASTING INSTALLATIONS

COPPER ROD

Date	Company & Location	Billet Section (Millimeters)	Caster	In-Line Rolling Mills
1982	Canada Wire and Cable Ltd. Montreal, Quebec CANADA	60 x 90	Mod.20.146	KRUPP 13-Stand Continuous Rod
1982	RODCO, Limited Skelmersdale, Lancashire ENGLAND	50 x 90	Mod.20.112	KRUPP 12-Stand Continuous Rod
1982	Phelps Dodge Corp. El Paso, Texas U.S.A.	60 x 150	Mod.20.146	KRUPP 16-Stand Continuous Rod
1982	Conticon Celaya MEXICO	60 x 90	Mod.20.146	KRUPP 13-Stand Continuous Rod
1984	National Iranian Copper Sar Cheshmeh IRAN	50 x 120	Mod.20.146	KRUPP 15-Stand Continuous Rod
1984	SECEM Cordoba SPAIN	50 x 90	Mod.20.112	KRUPP 12-Stand Continuous Rod
1984	Saudi Cable Co. Jeddah SAUDI ARABIA	50 x 58	Mod. 29.88	KRUPP 10-Stand Continuous Rod
[1986]	Xiangtan Cable Works Xiangtan, Hunan Province PEOPLE'S REPUBLIC OF CHINA	35 x 60	Mod. 29.88	KRUPP 9-Stand Continuous Rod
[1986]	Changzhou Smelter Changzhou, Jiangsu Province PEOPLE'S REPUBLIC OF CHINA	35 x 60	Mod. 29.88	KRUPP 9-Stand Continuous Rod
[1986]	Beijing Copper Plant Beijing Province PEOPLE'S REPUBLIC OF CHINA	55 x 58	Mod. 29.112	KRUPP 10-Stand Continuous Rod

CONTINUOUS CASTING INSTALLATIONS

COPPER ANODE PLATE

		Cast Width		Anode Suspension
1966	British Copper Refiners Prescot, Lanc.,ENGLAND	42" (1060mm)	Model 14	Hanger Bar
1972	Onahama Smelting & Refining Onahama, JAPAN	42" (1060mm)	Model 14	Pattern Cut
1978	Kidd Creek Mines, Ltd. Timmins, Ont., CANADA	45" (1150mm)	Mod.23.101	Pattern Cut
1979	Met. Hoboken-Overpelt Olen, BELGIUM	37" (940mm)	Mod.23.101	Cast-in Lug
1982	White Pine Copper Div. Copper Range Company White Pine, MI, U.S.A.	36" (910mm)	Model 23.75	Cast-in Lug
[1985]	IMI Refiners Ltd. Walsall ENGLAND	34" (864mm)	Model 23.75	Cast-in Lug

CONTINUOUS CASTING INSTALLATIONS

ZINC

Date	Company & Location	Cast Width	Caster	In-Line Rolling Mills
1965	Rheinisches Zinkwalzwerke Datteln GERMANY	43" (1100mm)	Model 14	DEMAG 5-Stand Tandem 2-High
1968	Compagnie Royale Asturienne des Mines, S.A. Auby FRANCE	43" (1100mm)	Model 14	ACHENBACH 2-Stand 2-High
1969	Ever Ready Co.(G.B.) Ltd. Newcastle ENGLAND	15" (380mm)	Model 20	ALBERT MANN Single Stand 2-High
1969	La Salle Rolling Mills (Formerly M&H) La Salle, Illinois U.S.A.	40" (1016mm)	Model 14	MESTA Single Stand Rev.4-High Hot/Cold
1969	Ball Corporation Greeneville, Tennessee U.S.A.	30" (760mm)	Model 14	WATERBURY FARREL Single Stand 2-High
1970	Vielle-Montagne S.A. Viviez FRANCE	48" (1219mm)	Model 14	SCHLOEMANN Single Stand MKW
1975	The Platt Bros. Co. Waterbury, Connecticut U.S.A.	10" (250mm)	Model 9	2-High
1980	Grillo-Werke A.G. Duisburg-Hamborn GERMANY	28" (710mm)	Model 20	DEMAG 3-Stand 2-High
1982	Eveready South Africa, Ltd. Port Elizabeth SOUTH AFRICA	11" (285mm)	Model 20	ALBERT MANN 2-Stand 2-High
1983	General Metals Company Cairo EGYPT	43" (1100mm)	Model 23	KRUPP Single Stand 4-High

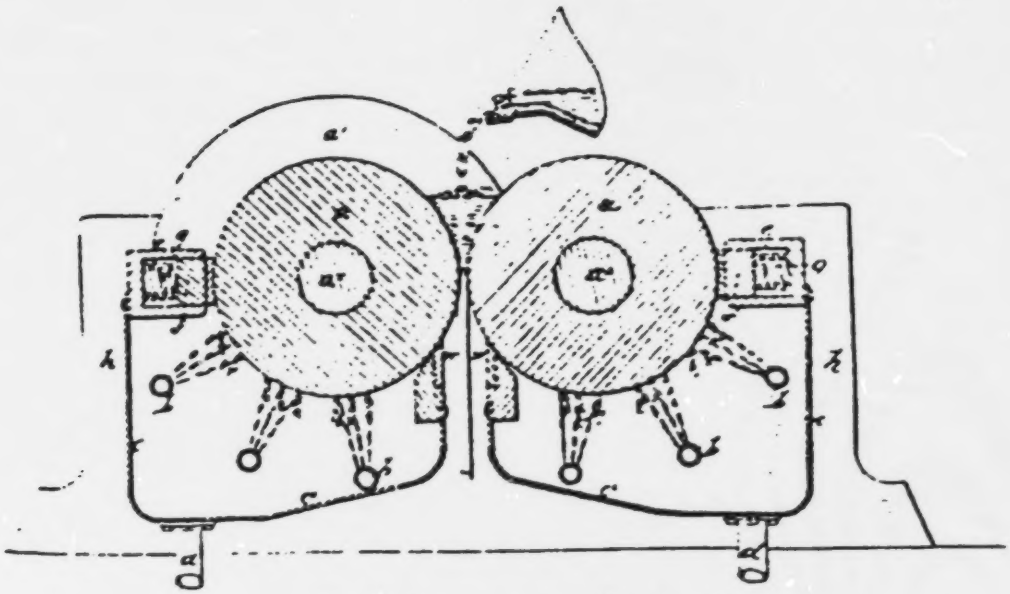
CONTINUOUS CASTING INSTALLATIONS

LEAD STRIP

Date	Company & Location	Cast Width	Caster	In-Line Rolling Mills
1975	General Motors Corp. Delco-Remy Division Fitzgerald, Georgia U.S.A.	10" (250mm)	Model 21	L.W. NASH Single Stand 2-High
1975	General Motors Corp. Delco-Remy Division Olathe, Kansas	3.3" (80mm)	Model 21	IBC 6-Stand 2-High

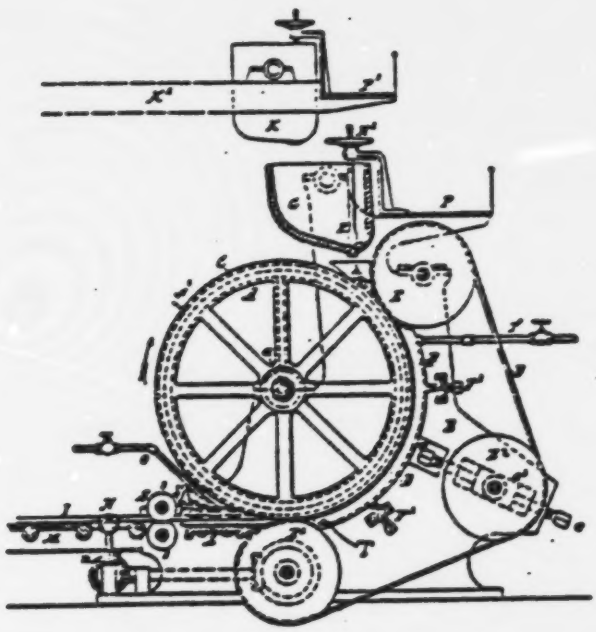
STEEL

1982	JAPAN	24" (600mm strip)	Model 20.101	Pilot Plant
1983	Krupp Industrietechnik Bochum GERMANY	2.75" x 7" (70mm x 180mm)	Model 25.154	Pilot Plant
[1986]	United States Steel & Bethlehem Steel Corp. (U.S. Dept. of Energy) Universal, Penn. U.S.A.	(Thin Strip)	Model 20 H/V	Pilot Plant



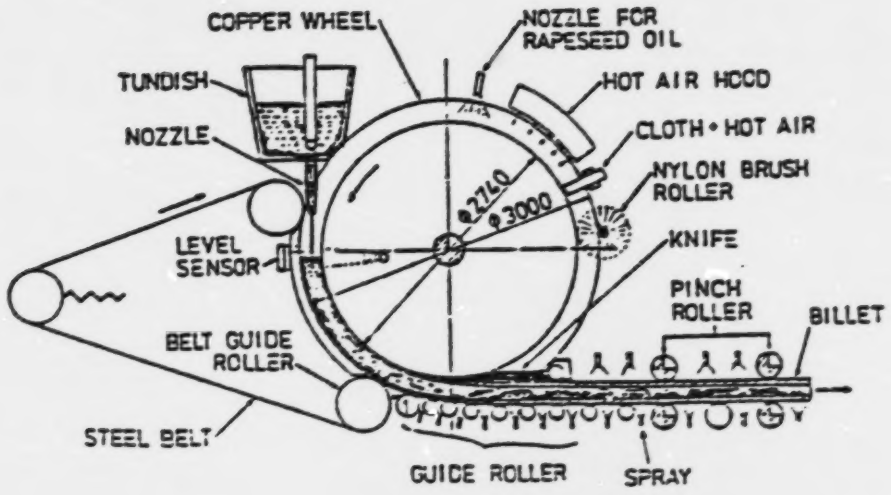
—Bessemer plan, from Patent 40053.

Figure 1



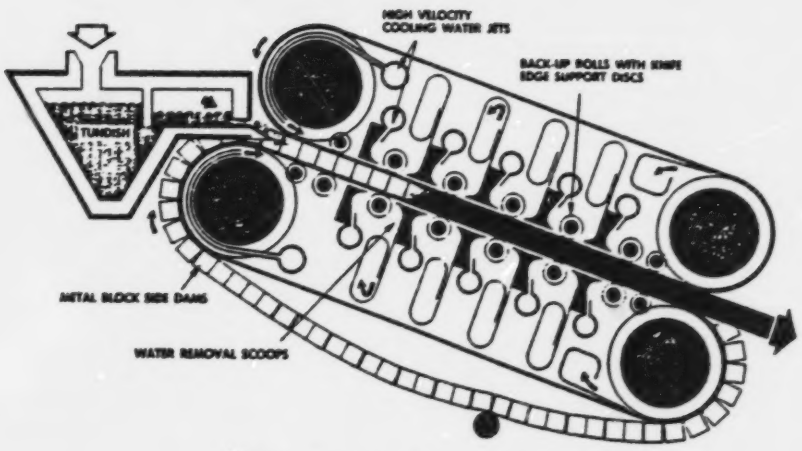
Schematic of wheel and belt caster by
F. H. Daniels (1887)

Figure 2



Schematic of a commercial wheel and belt continuous caster

Figure 3


HIGH VELOCITY COOLING WATER JETS
BACK-UP ROLLS WITH KNIFE EDGE SUPPORT DISCS
TUNDISH
METAL BLOCK SIDE DAMS
WATER REMOVAL SCOOPS

Cross Section of Hazelett Machine.

Figure 4

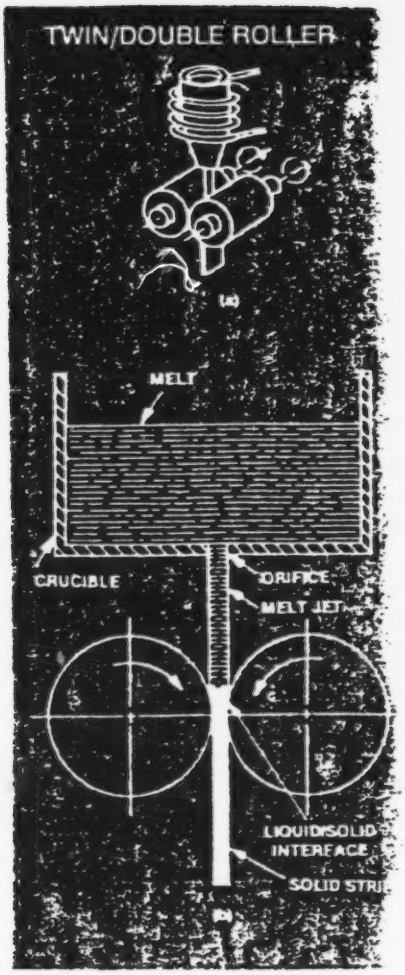

TWIN/DOUBLE ROLLER
MELT
CRUCIBLE
ORIFICE
MELT JET
LIQUID/SOLID
INTERFACE

Figure 5

PRESSURE
MELT SPINNING
LIQUID STREAM
CHILL BLOCK
SOLID STRIP
PLANAR FLOW CASTING
(a) SCHEMATIC OF PLANAR FLOW CASTING PROCESS
SOLID METAL
LIQUID METAL
COLD SUBSTRATE
DETAILED CONFIGURATION OF SLOTTED NOZZLE

Figure 9

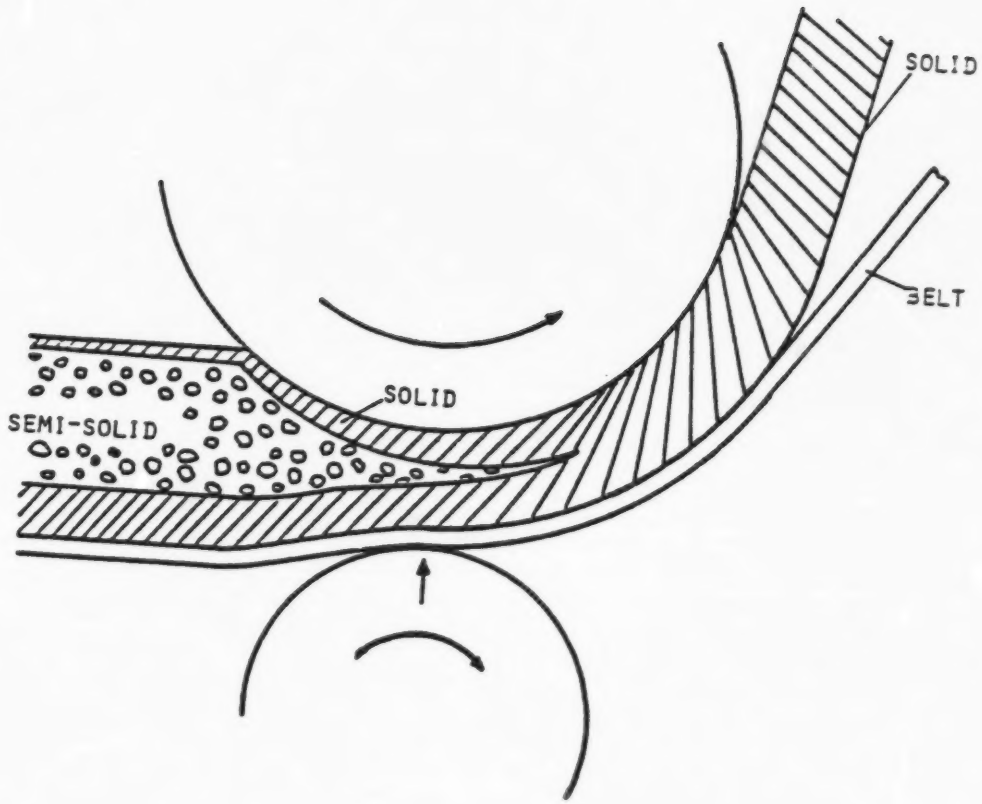


Figure 10 Continuous Casting of Strip by Rheocasting

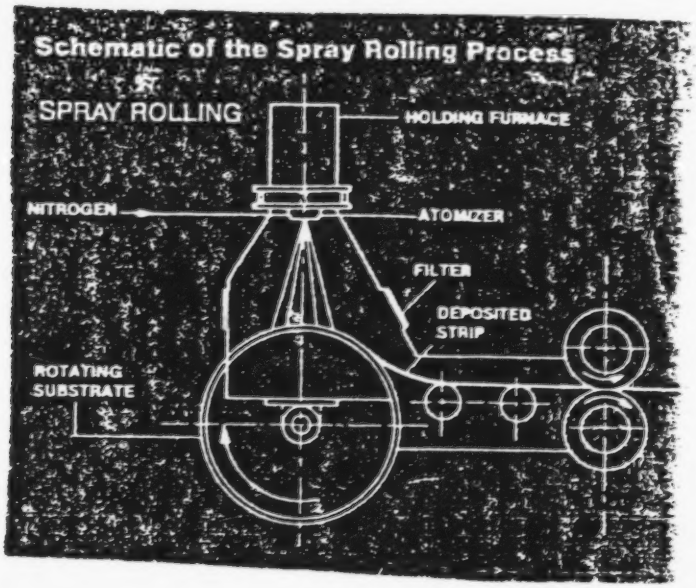


Figure 11

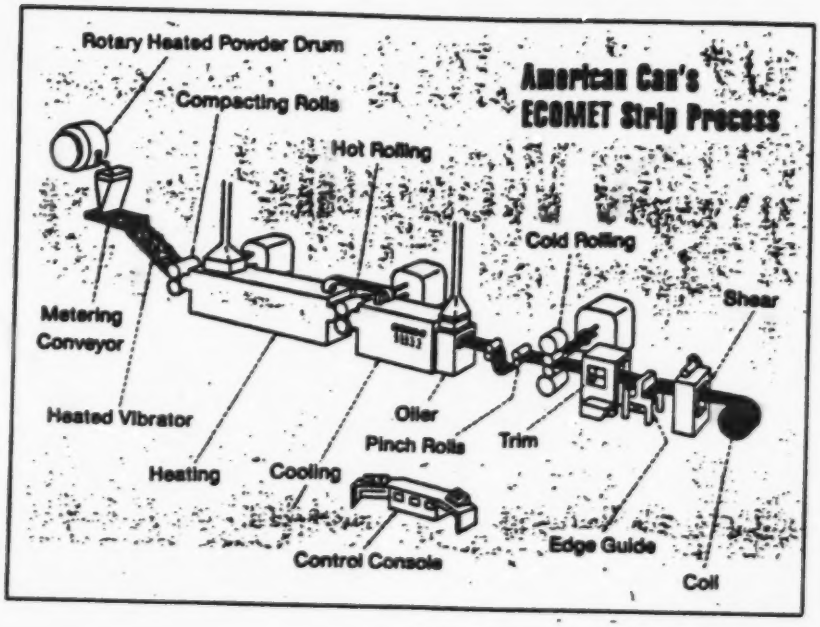
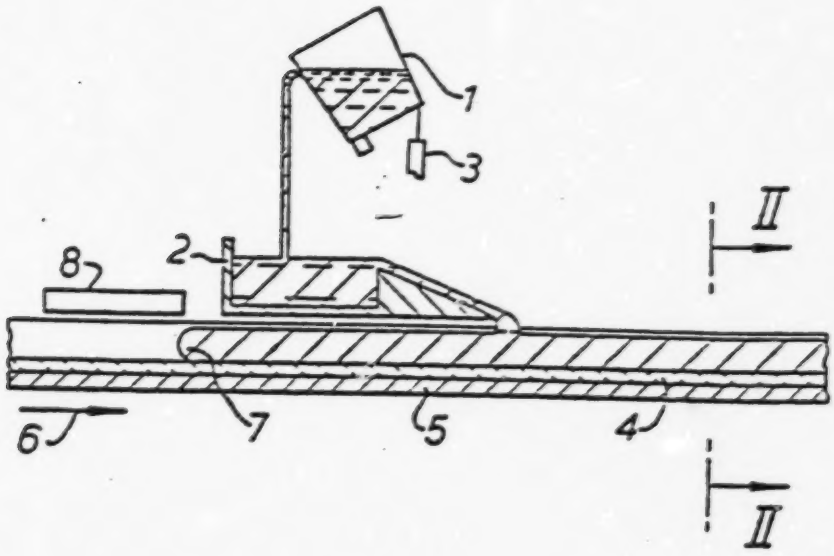


Figure 12
Powder-Rolling [18]



Schematic of a flat endless belt continuous caster with a magnetic field applied at point 7 to prevent backward flow of the liquid metal

Figure 13